Application of Multi-Frequency Synthetic Aperture Radar (SAR) in Crop Classification

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1. Introduction

The application of remote sensing to agriculture has traditionally focused on the use of data from optical sensors such as Landsat Thematic Mapper (TM) and SPOT. Due to cloud and haze interference, however, optical images are not always available at phenological stages important for crop discrimination. When gaps in data acquisition occur during critical growth periods, classification accuracies using optical data are often inadequate (Jewell, 1989; McNairn et al., 2002; Blaes et al., 2005). Mid to late season optical images are essential to achieve accurate crop classification, and this dependency on late-season data reduces the ability to deliver early-season crop acreage estimates (McNairn et al., 2008a, b; Shang et al., 2006, 2008). These constraints seriously impede the use of optical data for operational annual crop mapping. Unlike visible and infrared wavelengths which are sensitive primarily to plant biochemical properties, longer-wavelength microwave energy responds to the large-scale structural attributes of vegetation, including the size, shape and orientation of the leaves, stems, and fruits. The dielectric properties of the vegetation canopy also influence the magnitude of the radar backscatter. These diverse sensitivities suggest that the integration of data from optical and radar sensors will generate a synergistic effect. Recent research has found that this complementarity, in most cases, provides enough information to separate a wide variety of crop types when an integrated optical-radar dataset is used (McNairn et al., 2008a; Shang et al., 2006, 2008).

1.1 Airborne multi-frequency SAR applications to agriculture

Although an integrated optical-radar approach can consistently discriminate crops, the continued dependency on optical data, particularly in cloud-prone regions, is less than ideal for operational delivery of crop information. A radar-only approach to crop discrimination and acreage estimation would provide an operational advantage. Until recently, however, the successful development of a radar-only approach to crop classification has been hindered because of the availability of radar data with only limited dimensionality. Single frequencies, and for some sensors single polarizations, do not provide enough information for accurate discrimination even when multi-temporal acquisitions are exploited (Shang et al, 2006, 2008). Research campaigns based on airborne SAR acquisitions have explored the benefits of multi-frequency SAR for crop discrimination. The Jet Propulsion Laboratory's

AirSAR is a fully polarimetric SAR sensor operating at P- (0.45 GHz), L- (1.25 GHz), and C- (5.31 GHz) bands (Lee and Pottier, 2009). The value of multi-frequency fully polarimetric data has been demonstrated for many land applications. For example, Rao et al. (1993) studied multi-frequency (P-, L-, C-band) polarimetric AirSAR data over corn fields. It found that the mean polarization phase difference increases with increasing wavelength. Lemonie and associates (1994) used the AirSAR data to study the contribution of multi frequency radar to increased agricultural class separabilities. The study by Baronti and associates (1995) carried out a three-frequency (P-, L-, and C-band) AirSAR data analysis. It found that P-band data are effective only in discriminating broad classes of agricultural landscapes. The integration of L- and C-band helps reveal finer class details.

Much research on the advantages of multi-frequency SAR has also been conducted with radar scatterometers. For example, Snoeij et al. (1990) used C- and X-band airborne SAR data to study the general behaviour of the radar signature of different European test sites as a function of frequency. The study conducted by van Leeuwen (1992) used six-frequency (L-band at 1.2 GHz; S-band at 3.2 GHz; C-band at 5.3 GHz; Ku1-band at 13.7 GHz; and Ku2-band at 17.3 GHz) radar scatterometer data over beet and wheat fields to examine the physical meaning of radar model (CLOUD-model: Attema & Ulaby, 1978) parameters in relation to crops. More recently Inoue et al. (2002) studied multi-frequency (Ka-, Ku-, X-, C- & L-band) radar backscattering signatures over paddy rice fields and their relationship with rice canopy growth variables. This research demonstrated that the backscatter coefficients of higher frequency bands (Ka and Ku) are highly correlated with the weight of heads. Lower frequency bands such as L-band, are better correlated with fresh biomass while C-band is better correlated with leaf area index.

1.2 Space-borne multi-frequency SAR applications to agriculture

Airborne SAR systems enabled radar scientists to develop methods to derive information of interest from multi-frequency and multi/full-polarization SAR, often under controlled experimental conditions. Airborne sensors provide a far greater signal to noise ratio and much higher spatial resolution compared with spaceborne sensors. However, these airborne platforms are not suited for large scale operational campaigns. With their wide swaths and repeat orbits, spaceborne sensors provide a cost effective solution for operational activities.

Since the launch of the first spaceborne radar system in 1965, Radar Evaluation Pod (REP), many spaceborne radar sensors have been launched (Lacomme et al., 2001). Earth Resources Satellite (ERS-1 launched in 1987 and ERS-2 launched in 1995) data have been used to develop many applications in agriculture, wetlands and forestry (Ban & Howarth, 1999; Bouman et al., 1992; Engdahl et al., 2001; Kohl et al., 1994; Michelson et al., 2000; Paudyal et al., 1995; Wang et al., 1998). The frequency-polarization (C-HH) of RADARDAT-1 (launched in 1995) was selected to maximize information for marine applications including sea ice and ocean features. Nevertheless, scientists developed the use of these data for a wide range of land applications including agriculture (McNairn et al., 1998a, b, c; Phoompanich et al., 2005; Ribbes & Toan, 1999; Shang et al., 2006).

The next generation European C-Band sensor, ASAR, has further advanced the use of SAR for agricultural mapping. The availability of dual like-polarizations (HH-VV) or dual like-cross polarizations (HH-HV or VV-VH) with ASAR, assists in providing more information on vegetation type and condition. Radar backscatter varies from one polarization to another since interaction is dictated by the transmitting polarization relative to the horizontal and vertical structure of the canopy. Consequently sensors which have polarization diversity provide more information on both crop structure and crop condition. The launch of ALOS PALSAR (L-band: 1.27 GHz) in 2006, followed by TerraSAR-X (X-band: 9.6 GHz) and RADARSAT-2 (C-band: 5.405 GHz) in 2007, marked the beginning of the multi-frequency spaceborne SAR era. Availability of data from this suite of satellites has accelerated the use of SAR for land applications. When used together, a multi-frequency dataset from multiple SAR platforms holds the promise to provide exceptional information for agriculture. Using a Canadian example, this chapter demonstrates the application of integrated L-, C-, and X-band SAR for crop mapping.

2. Study sites and data collection

2.1 Study sites

In 2006 Agriculture and Agri-Food Canada (AAFC) established two research sites close to their Ottawa (Ontario, Canada) research station. The Canadian Food Inspection Agency (CFIA) site is a controlled experimental site within the city of Ottawa (centred at 45°13′N, 75°46′W). The second site, Casselman, is a region of private land ownership (centred at 45°37′N, 75°01′W) approximately 50 km east of Ottawa. Both sites support non-irrigated dry land farming with one crop grown during the relatively short May to September growing season. The size of the fields in this part of Canada tends to be relatively small, 20 ha on average. These sites are typical of the crop mix found in this part of Canada, with production acreages primarily consisting of corn, soybean, cereal and pasture-forage.

2.2 Satellite data collection

(a) CFIA site

Satellite data were acquired from optical sensors (Landsat-5) as well as SAR sensors (RADARSAT-1, Envisat-ASAR, and ALOS PALSAR) throughout the 2006 growing season. Acquisitions were targeted to capture crop growth stages of importance for crop discrimination using optical and SAR sensors (Table 1).

Date	Resolution (m)	Mode	Polarization	Incidence Angle
Landsat-5 TM				
June 5	30			
July 7	30			
August 22	30			
Envisat ASAR				
May 27	30	IS3	VV, VH	25.8° - 31.2°
June 9	30	IS1	VV, VH	14.5° - 22.1°
July 1	30	IS3	VV, VH	25.8° - 31.2°
July 14	30	IS1	VV, VH	14.5° - 22.1°
August 5	30	IS3	VV, VH	25.8° - 31.2°
September 18	30	IS4	VV, VH	30.8° - 36.1°

RADARSAT-1				
May 18	30	S1	HH	24° - 31°
July 5	30	S1	HH	24° - 31°
August 22	30	S1	HH	24° - 31°
ALOS PALSAR				
May 19	10	PLR	Polarimetric	21.5°
July 4	10	PLR	Polarimetric	21.5°
August 19	10	PLR	Polarimetric	21.5°

Table 1. Satellite data acquired over CFIA during the 2006 growing season

(b) Casselman site

Optical and radar satellite data were collected over the Casselman site during the 2008 growing season. No cloud-free (less than 20% cloud cover) Landsat data were available due to poor weather conditions throughout the summer of 2008. The SPOT sensor was programmed in two week windows through the entire 2008 season. This acquisition strategy yielded four SPOT-4 images. Six TerraSAR-X scenes were also acquired. Due to the late start of the TerraSAR-X project, X-band data acquisition did not commence until mid July. Table 2 gives the details of each satellite acquisition.

Date	Resolution (m)	Mode	Polarization	Incidence Angle
SPOT-4				
June 5	20			
July 7	20			
August 22	20			
RADARSAT-2				
May 27	10	FQ19	quad-pol	38.3° - 39.8°
June 9	10	FQ19	quad-pol	38.3° - 39.8°
July 1	10	FQ19	quad-pol	38.3° - 39.8°
July 14	10	FQ19	quad-pol	38.3° - 39.8°
TerraSAR-X				
July 19	6	Stripmap	VV, VH	43.6° - 44.6°
July 30	6	Stripmap	VV, VH	43.6° - 44.6°
August 10	6	Stripmap	VV, VH	43.6° - 44.6°
August 21	6	Stripmap	VV, VH	43.6° - 44.6°
August 26	6	Spotlight	HH, VV	53.9°
September 1	6	Stripmap	VV, VH	43.6° - 44.6°

Table 2. Satellite data acquired over Casselman during the 2008 growing season

2.3 Ground data collection

For both sites, ground truth observations were collected twice over the growing season, once in early July and once in mid August. The second visit provided an opportunity to check for errors which might have occurred during the first field visit. During the second visit, variations in crop growth condition, harvesting, and emergence of under seeded crops were also noted. Underseeding is a cropping system where a primary species is seeded with a successive species that emerges at the end of the primary species growth cycle, for instance, where annual cereal crops are underseeded with a perennial forage crop such as alfalfa. Wheat in this region is usually harvested between late July and mid August depending on the planting date. Underseeded wheat fields are thus characterized by rapid growth of forage after wheat harvest. Harvesting of corn and soybean typically occurs near the end of October.

In 2006, a total of 240 fields were visited. Table 3 gives details on the number of fields surveyed per crop.

Crop Type	Number of Training Fields	Number of Testing Fields
Cereal	16	17
Corn	35	35
Soybean	30	30
Forage/Pasture	38	39

Table 3. Ground truth data used for CFIA 2006 crop classification

For the Casselman site, a total of 247 fields were surveyed during the 2008 growing season. The distribution of field surveyed is documented in Table 4.

Crop Type	Number of Training Fields	Number of Testing Fields
Cereal	17	18
Corn	45	45
Soybean	41	41
Forage/Pasture	33	34

Table 4. Ground truth data used for Casselman 2008 crop classification

3. Data pre-processing

3.1 Atmospheric correction of optical data

Atmospheric correction was applied to all optical data to retrieve the at-surface reflectance using the Atcor algorithm in PCI software (Richter, 2004). The Atcor algorithm uses the MODTRAN 4.2 radiative-transfer code for the radiance to reflectance conversion (Champagne et al., 2005).

3.2 Speckle filtering of SAR data

Speckle is an inherent phenomenon for coherent systems such as SARs. To suppress speckle, adaptive radar filters should be applied prior to classification of SAR data. All ALOS PALSAR, RADARSAT-2, and TerraSAR-X data were speckle filtered, using a 5 X 5 Gamma-MAP filter.

3.3 Geometric correction and co-registration

For the purposes of integrating the various data sources, and in order to facilitate comparisons with ground data, all of the Landsat, SPOT, PALSAR, TerraSAR-X and RADARSAT-2 data were geocorrected and registered to the same coordinate system (UTM). A nearest neighbor re-sampling method was adopted with an output resolution of 10 m.

3.4 Trainning and validation site selection

To reduce bias, the training and validation pixels were selected from different fields. For each crop type, training and validation fields were selected randomly from the total ground truth data set in ArcGIS (Figure 1). As a first step, a 10m buffer was applied to each field boundary. The pixels within this boundary buffer zone were excluded from training and validation to reduce contamination from headlands and mixed pixels. Half of the fields surveyed were randomly selected and used for training the classification algorithm. The remaining fields were reserved for quantifying the accuracy of the classification. As a result, there was no overlap between training and validation pixels.

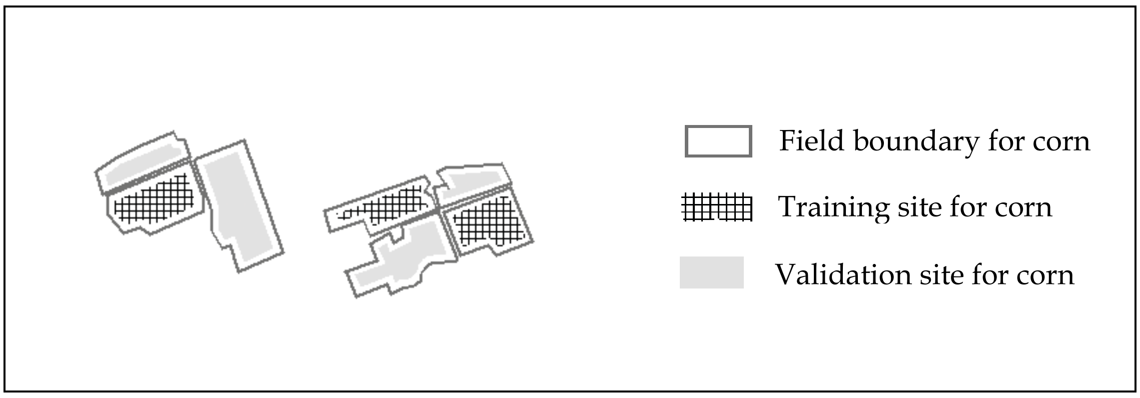

Fig. 1. An example showing the spatial arrangement of the training and validation fields.

4. Methodology

The type of classification methods used can greatly impact the classification results. When adequate ground truth data are available, supervised classification approaches generally produce better results relative to unsupervised classifications. Consequently for this study, a supervised classification was selected. The choice of classification algorithm is influenced by many factors, including data requirement, sensitivity to variation of training data, and computational requirements. This study adopted a supervised decision tree (DT) classifier (McNairn et al., 2008a). DT takes a sequential classification approach (Pal & Marther, 2003). This non-parametric classifier is appropriate for use with SAR data, which typically are not normally distributed. A DT classifier can also handle data gaps which are commonly encountered when cloud masking is applied to optical data.

AAFC developed an in-house DT graphical user interface (GUI) which integrates PCI Geomatica and the See5 softwares (Rulequest Research, 2008). The DT classifier was run using boosting over 5 trials with a global pruning of the model of 25%. All classifications were performed on a per pixel basis without a null class.

Pixel-based classifications often result in a salt-pepper appearance, especially when radar data are used. Therefore a post-classification filter was applied to the resultant maps. For this study, spatial filtering was accomplished using segments created witin eCognition and assigning the mode class to each segment. The filtered maps are visually more consistent and exhibit increased classification accuracies.

5. Results and discussion

5.1 Single-frequency classification performance comparison

The classification accuracies for single frequency imagery are being discussed in this section. DT classifications were run using single frequencies (L- and C-band) to assess which radar wavelength provides the highest accuracies. To facilitate this comparison, only L- and C-band data collected close in time were used.

For the CFIA site, three pairs of data collected in 2006 were compared using data with the same polarization. Comparisons were restricted to pairs of data acquired within a seven-day window to avoid significant variations caused by plant growth between the two acquisition dates.

Sensors	Frequency	Polarization Used for Comparison	Date	Pasture/ Forage	Soybean	Corn	Wheat	Overall Accuracy
PALSAR	L-band	VV/VH	May 20	24.1	57.5	84.1	1.4	49.7
ASAR	C-band	VV/VH	May 27	60.0	50.7	81.7	4.9	55.7
PALSAR	L-band	VV/VH	July 5	18.0	67.0	86.7	11.8	54.0
ASAR	C-band	VV/VH	July 1	70.6	65.2	88.8	33.0	68.1
PALSAR	L-band	HH	May 20 July 5	55.8	49.3	83.8	9.2	54.8
RSAT-1	C-band	HH	May 18 July 5	79.8	54.0	61.0	8.1	52.8

Table 5. Comparison of single- and two-date PALSAR, ASAR, and RADARSAT-1 2006 crop classification accuracies (producer's) over the CFIA site

For the two acquisition windows (late May and early July) and considering overall accuracy, C-band data performed better than the L-band data using VV and VH polarizations. For larger biomass crop such as corn, the two frequencies (VV/VH) are comparable. For lower biomass crops, such as forage, the shorter wavelength C-band performs better.

When two dates of HH SAR data are used (one in May and one in July), L-band produced an overall accuracy of 54.8%, slightly higher than C-band's 52.8%. For larger biomass corn crops, L-band performs significantly better than C-band with accuracies of 83.8% and 61.0%, respectively. For lower biomass crops, such as cereal and pasture-forage, L-band was less effective. With lower biomass and a less random vegetation structure, greater penetration into the crop canopy due to the longer wavelength can be expected, which would include greater contribution from the underlying soil, as well as from vegetation-soil interactions (Freeman & Durden, ; Hill et al.,). C-band outperforms L-band for lower biomass crops.

For the Casselman study site, two pairs of TerraSAR-X (TSX) and RADARSAT-2 (RSAT-2) imagery collected close in time were selected for comparison. Table 6 documents the classification results derived using data acquired over Casselman during the 2008 growing season.

Sensors	Frequency	Polarization Used for Comparison	Date	Pasture/ Forage	Soybean	Corn	Wheat	Overall Accuracy
TSX	X-band	VV/VH	July 16	69.1	58.2	48.0	85.2	59.9
RSAT-2	C-band	VV/VH	July 19	47.1	64.7	50.7	42.8	54.2
TSX	X-band	VV/VH	August 9	59.1	79.4	71.0	61.8	71.0
RSAT-2	C-band	VV/VH	August 10	39.6	73.8	56.2	36.8	57.4

Table 6. Comparison of single-date TerraSAR-X and RADARSAT-2 crop classification accuracy (producer's) over the Casselman site from the 2008 growing season

For both acquisition windows (mid July, early August), X-band data outperformed the C-band data. When comparing overall accuracies, the mid July X-band data produced a crop map with an accuracy 5.7% higher than for C-band data acquired only three days later. Comparing data acquired in early August, X-band provided significantly better accuracies - an overall accuracy of 71% or 13.6% higher than the C-band data. In August the X- and C-Band data were acquired only one day apart. Examining the individual class accuracies, X-band performed better in identifying all crop types later in the season. Among all crop types, X-band provided dramatically higher accuracies for wheat. A 42.4%increase for mid July and 25% increase for early August are noted for the wheat class, when X-band results are compared with those of C-band. For the same wheat class, X-band data also performed better than C-band later in the growing season. At mid season (mid July), results derived from X- and C-band are similar for corn, with a difference of less than 3%.

5.2 Multi-frequency classification comparison

To evaluate the benefits of a multi-frequency SAR approach for crop classification, four datasets from the CFIA site were analyzed. Table 7 provides the classification accuracies derived using single-frequency (L- or C-band) and two-frequency (L- and C-band) approaches.

Sensors (Date)	Frequency	Polarization Used for Comparison	Pasture/ Forage	Soybean	Corn	Wheat	Overall Accuracy
1 ALOS (May20)	L-band	VV/VH	24.1	57.5	84.1	1.4	49.7
1 ASAR (May27)	C-band	VV/VH	60.0	50.7	81.7	4.9	55.7
1 ASAR (May27) + 1 ALOS (May20)	C- & L-band	VV/VH	60.9	61.9	70.8	40.8	60.6
1 ALOS (July 5)	L-band	VV/VH	18.0	67.0	86.7	11.8	54.0
1 ASAR (July 1)	C-band	VV/VH	70.6	65.2	88.8	33.0	68.1
1 ASAR (July 1) + 1 ALOS (July 5)	C- & L-band	VV/VH	61.1	77.6	92.4	48.4	73.9

2 ALOS (May20, Jul5)	L-band	HH	55.8	49.3	83.8	9.2	54.8
2 RS1 (May18, Jul5)	C-band	HH	79.8	54.0	61.0	8.1	52.8
2 ALOS (May20, Jul5) + 2 RS1 (May18, Jul5)	C- & L-band	HH	87.5	73.2	82.1	24.8	69.8
2 ALOS (May20, Jul5)	L-band	VV/VH	54.2	67.4	83.6	37.5	64.7
2 ASAR (May27, Jul1)	C-band	VV/VH	74.1	61.2	91.6	52.6	72.2
2 ASAR (May 27, Jul 1) + 2 ALOS (May20, Jul 5)	C- & L-band	VV/VH	72.4	84.5	95.7	69.6	82.9

Table 7. Producer's accuracies using multi-frequency SAR classifications from the 2006 data acquired over CFIA

Results in Table 7 clearly confirm the benefits of a multi-frequency solution for crop identification. For a single-date dual-polarization (VV/VH) comparison, there is an increase of 4.9% in overall accuracy in late May compared to result derived using ASAR alone. When compared with result derived from May ALOS, there is an increase of 10.9%. When early July L- and C-band data are integrated together in the classifier, a similar improvement in accuracy (5.8%) was observed. When multiple dates (one in May and one in July) of L- and C-band were used a 15% gain in accuracy was observed, even though only a single polarization (HH) was used. Two dates of dual-frequency and dual-polarization SAR from PALSAR (L-band) and ASAR (C-band) produced a map with an overall accuracy of 82.9%.

For the Casselman site, comparisons were made between classifications using a single frequency (C- or X-band) and results achieved by integrating these two frequencies (Table 8). The multi-temporal X-band data on its own was capable of identifying crops with an overall accuracy of 84.9%. Consequently, adding C-band SAR to the classification brought only modest improvements in overall accuracy. Nevertheless C-band did assist in boosting accuracies for most individual crop classes.

Sensors (Date)	Frequency	Polarization Used for Comparison	Pasture/ Forage	Soybean	Corn	Wheat	Overall Accuracy
4 RSAT-2	C-band	VV/VH	66.2	82.9	76.1	64.0	75.4
5 TerraSAR-X	X-band	VV/VH	83.2	83.6	87.3	84.1	84.9
4 RSAT-2 + 5 TerraSAR-X	C- & X-band	VV/VH	84.1	86.8	89.9	85.6	87.3

Table 8. Producer's accuracies of multi-frequency SAR classification from 2008 growing season over Casselman

6. Conclusions and future research

A multi-year and multi-site study by Agriculture and Agri-Food Canada demonstrated the improvements brought by integrating multiple frequencies (L-, C-, and X-band) of SAR data for crop classification. Penetration into the crop canopy is dependent upon SAR frequency and results indicate that the differences in this depth between frequencies are advantageous for crop identification. The case study presented here concludes that when multi-temporal multi-frequency SAR data are used, satisfactory crop classification (above 85% accuracy) can be achieved using a SAR-only dataset.

Even with these promising results, further improvements in accuracy would be desirable prior to implementing a radar-alone solution for crop classifications. The acquisition planning associated with the datasets used in the research was limited by several factors. TerraSAR-X data collection did not begin until mid season due to a late start in the project. In future growing seasons, a more complete data set will be collected. This study also did not permit comparisons among all three frequencies as TerraSAR-X, ASAR, RADARSAT and PALSAR data were not all collected over either site. The programming of PALSAR in concert with TerraSAR-X and RADARSAT-2 was not successful. In future growing seasons, all three sensors have been programmed over the Casselman site. These methods will also be evaluated in future growing seasons over a third site in the Canadian prairies, which will represent a more complex cropping system with a greater variety of crops. Lastly, acquisitions of data in RADARSAT-2's polarimetric mode will permit assessment of polarimetric parameters derived from multi-frequency SAR for improved crop classification.

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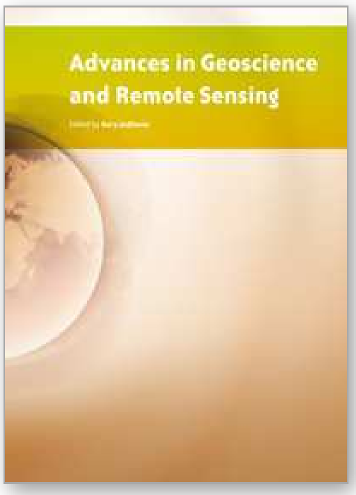

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Remote sensing is the acquisition of information of an object or phenomenon, by the use of either recording or real-time sensing device(s), that is not in physical or intimate contact with the object (such as by way of aircraft, spacecraft, satellite, buoy, or ship). In practice, remote sensing is the stand-off collection through the use of a variety of devices for gathering information on a given object or area. Human existence is dependent on our ability to understand, utilize, manage and maintain the environment we live in - Geoscience is the science that seeks to achieve these goals. This book is a collection of contributions from world-class scientists, engineers and educators engaged in the fields of geoscience and remote sensing.

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